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Comparison of numerical analysis models for shielding failure of transmission lines

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ABSTRACT

The shielding failure is the occurrence of a lightning stroke that bypasses the overhead shielding wires and strikes on the phase conductors. The improvement of the shielding effect of transmission line to lightning is one of key problems in transmission line design. Some analysis models for shielding failure performance were proposed and discussed, mainly including the traditional electrogeometric model (EGM) and improved EGM, the leader progression model (LPM). The paper compares the results of shielding failure rate, lightning current range and location region for shielding failure by numerical calculation applying the three models. The influence of ground slope angle, voltage class of transmission line and protection angle of ground wire is also taken into account.

1. Introduction

The improvement of the shielding effect of transmission line to lightning is one of key problems in transmission line design. Some numerical analysis models for analysis of shielding failure performance were proposed and discussed. The EGM model [1,2] based on the concept of striking distance is the most traditional, simple and effective method for lightning performance analysis of transmission lines. The striking distance means the critical distance of the downward leader tip of lightning and the struck object leading to shielding failure. Several researchers including Wagner [3–5], Yong [6], Armstrong and Whitehead [7], Brown and Whitehead [1] have contributed to the EGM model on the striking distance of the flash.

The striking distances contain striking distances for phase conductor, shield wire and ground, which are equal in original EGM model. However, some researchers improved the original EGM by differing the three distances.

Dellera et al. put forward the leader progression model (LPM) based on lightning leader theory and long air gap discharge process [9], and the details of lightning leader movement from cloud to line and upward leader inception criteria are investigated by some researchers [11], and LPM which was called as numerical analysis method was also discussed in [14].

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The purpose of this paper is to compare the analyzed results of different analysis models for shielding failure performance, mainly including the traditional electrogeometric model (EGM) and improved EGM, the leader progression model (LPM). This paper is the extended version of our paper [26] in APL 2011.

2. Numerical analysis model

2.1. Traditional EGM and improved EGM models

The IEEE recommended the striking distance for the shield wire r_s is [2]

$$r_s = 10I^{0.65} \tag{1}$$

Some researchers assumed the striking distances for phase conductor r_c, shield wire r_s and ground r_g are equal as shown in formula (1), while some scholars improved the original EGM model by differing the three striking distances. The striking distance for ground r_g can be calculated by

$$r_g = k_g r_s \tag{2}$$

where k_g is the ratio of the striking distance for ground and for overhead ground wire (also called as shield wire). If there are easily struck objects or projecting objects on the ground, k_g can be selected as 1. But if the ground is flat enough, the suggested value of k_g is in the range of 0.6–1.0 [8].

Fig. 1 gives the schematic illustration of the EGM model. With regards to a lightning with current magnitude of I_i, the corresponding striking distances r_s, r_g and r_c are calculated by formulas (1)–(4).

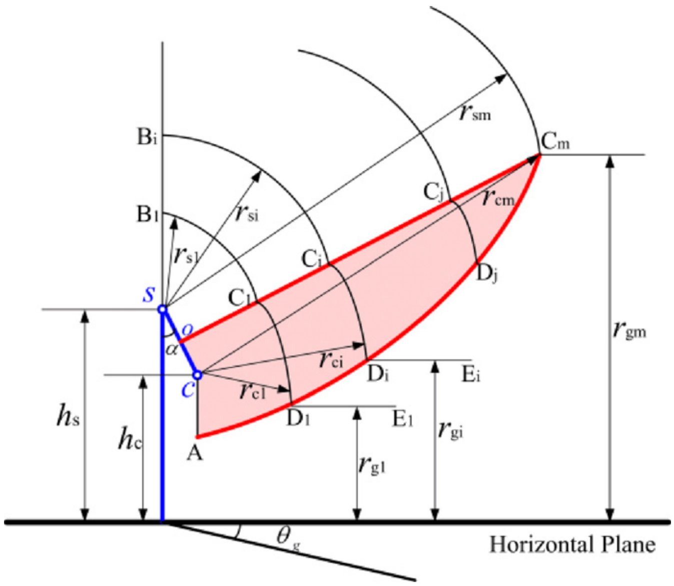

Fig. 1. The schematic diagram for analysis of shielding failure in EGM model.

The arcs B_iC_i and C_iD_i are circled with center of s and c and radius of r_s and r_c respectively, and C_i is the intersecting point of the two arcs. Drawing a straight line D_iE_i paralleling to the ground with a distance of r_g, and the intersecting point is D_i. The curve oC_m formed by points C_i and curve AD_iC_m formed by points D_i divide the whole space into three regions, where the inner area in shadow in Fig. 1 is the region for occurrence of lighting shielding failure, that is, the area for lightning striking phase conductors.

Due to results for high voltage transmission lines are less accurate [10] applying EGM model, improved EGM models were proposed [12,13]. Many scholars had proposed modified formulas of striking distance to consider the influence of the operation voltage and the height of transmission tower. IEEE recommended the value of k_g or r_g [9] shown in formula (3), and the suggested value of r_c considering the operating voltage is given in formula (4).

$$r_g = \left\{ \begin{array}{ll} [3.6 + 1.7\ln(43 - h_c)]I^{0.65}, & h_c < 40\,\text{m} \\ 5.5I^{0.65}, & h_c \geq 40\,\text{m} \end{array} \right\} \tag{3}$$

$$r_c = 1.63(5.015I^{0.578} - 0.001U_{ph})^{1.125} \tag{4}$$

2.2. LPM model

In LPM model, the downward leader of lightning is usually assumed as a line segment filled with charge. The electric field around the grounded object, which is induced by progression of the downward leader, is calculated by the charge simulation method (CSM). When the induced electric field or induced voltage on the object exceeds a critical value, an upward leader is initiated from the surface of the object. The upward leader approaches toward the head tip of the downward leader. When the gap between two leader tips is completed, a final jump takes place, and the lightning channel is bridged and connected.

The charge within the cloud is denoted as Q_{cloud}. The charge distribution in the cloud is extremely complex and the influence of the cloud charge on the space electric field becomes less when the downward leader gradually approaches the ground, for simplicity, the cloud charge is usually replaced by a round plate or sphere filled with charge with homogeneous distribution. This paper adopts a two-polar point charge structure shown in Fig. 2 to simulate the cloud charge, and not considering the horizontal discharge within the cloud.

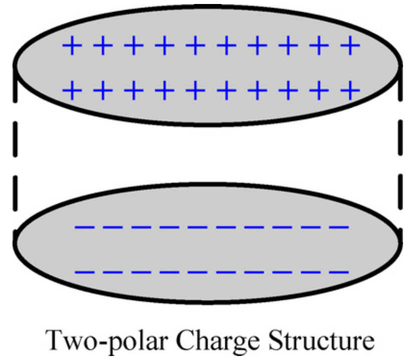

Fig. 2. The structure of charged cloud.

The LPM model adopted in this paper assumes the leader charge has a homogeneous distribution, and the relationship [28] of the leader charge density q versus lightning return stroke current I is:

$$q = 3.3 \times 10^{-6}\sqrt{I^2 + 500I} \tag{5}$$

2.2.1. Upward leader criterion

In our analysis model, we supposed the lightning would strike an object if there is an upward-directed leader from the surface of this object. There are three criteria to judge if an upward leader generates from the target.

a. Three gap X, gap Y and gap Z with a constant length L are assumed for ground, phase conductor and ground wire, respectively, as shown in Fig. 3. If the potential difference of any gap exceeds the air's critical breakdown voltage of the gap, an upward leader will incept from the corresponding target [16].
b. When the average electrical field intensity between the tip of downward leader and the target exceeds air critical breakdown electrical field intensity, upward leader will incept from the corresponding target.
c. For horizontal conductor, a formula to estimate the induced voltage essential for continuous positive leader inception was proposed by Rizk [13] as shown in formula (6).

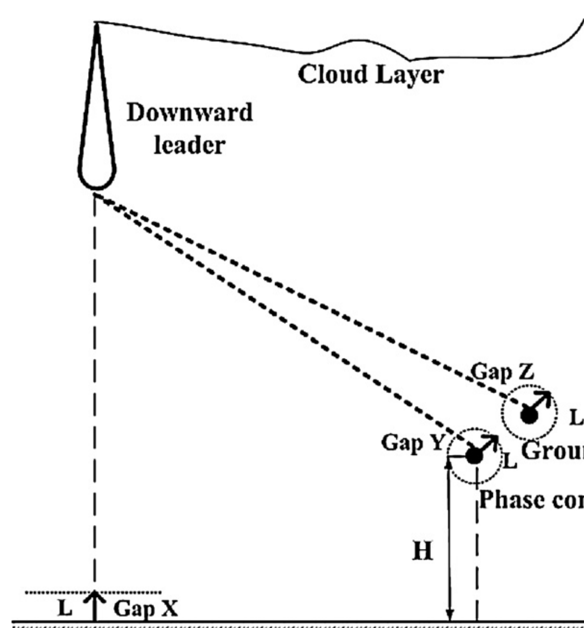

Fig. 3. Model to analyze the upward leader.